

Core Analysis and Correlation to Seismic Attributes, Weyburn Midale Pool, Southeastern Saskatchewan

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Abstract

The Reservoir Characterization Project at the Colorado School of Mines has acquired multi-component time-lapse data at the Weyburn Midale Pool to monitor the CO₂ flood for enhanced recovery. Using the time-lapse data, geophysically rendered maps of the pool have been created. Although specific attributes aid in the interpretation of certain shapes or anomalies that may be associated with the CO₂ injection, particular questions about the geology remain unanswered. By studying cores and logs, a detailed geological model can be generated that will provide a local focus for correlation to the seismic interpretations.

In the Mississippian Midale Vuggy unit, the vertical and lateral distributions of shoal and intershoal strata show that the shoals are not lithologically interconnected and are separated by mudstones representing intershoal areas. Earlier fracture analysis and first-hand observation of the cores indicate rocks from intershoal areas are more likely to be fractured. Therefore, although intershoal rocks are less porous and permeable, fractures within them may act as fluid conduits from one shoal to another. The contact between the Midale Marly and the Midale Vuggy may have been an exposure surface, which now has drastically different porosity and permeability values that prevent fluid from flowing from one zone to another. Another contributory factor to poor flow is the presence of anhydrite that infills many vugs and cements numerous fractures. Replacement metasomatic anhydrite commonly fills fractures and permeates outwards into the matrix of the shoal facies in the lower Vuggy.

Preliminary analysis of selected seismic attributes allows for several possible geological interpretations. For example, analysis of seismically rendered p-wave amplitudes may show a correlation to differences in reservoir-quality rocks within the Marly zone; an interval of thinly interbedded limestone and dolostone at one well and a 6.1 m (20 ft) thick layer of massive, bioturbated skeletal dolostone at another well are situated in areas with different p-wave amplitude anomalies. Also, change in p-wave acoustic impedance maps indicates that the injected CO₂ is not entering the Marly, but is finding a pathway, possibly through vertical fractures, that allows fluids to migrate downwards in to the underlying Frobisher Beds, a process which may account for oil staining seen below the Frobisher contact. This oil staining is evidence that no basal seal is present at that well.

To integrate geology and geophysics, rock properties known at each well location can be cross-plotted with seismic attributes. If linear trends are produced, a direct relationship between the geology and the specific attribute is inferred. This will lead to more accurate interpretation of ambiguous anomalies.

Keywords: *Mississippian, Midale, Marly, Vuggy, Frobisher, Williston Basin, multi-component time-lapse, seismic attributes, reservoir characterization, carbonate tidal flat, Weyburn Midale Pool.*

1. Introduction

Reservoir characterization requires the integration of geophysics, geology, and petroleum engineering. Understanding the rock properties and facies distribution is especially important in a reservoir with low vertical seismic resolution, as is the case for the Weyburn Midale Pool. By studying cores on a local scale, the reservoir characterization can be refined, and the seismically rendered geophysical anomalies can be explained. The Reservoir Characterization Project (RCP) at the Colorado School of Mines has been using multi-component time-lapse seismic data to characterize and monitor enhanced recovery of the oil-producing Midale Beds at the Weyburn Field. From October 2000 to October 2002, three multi-component seismic surveys were conducted at Weyburn.

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2. Geology

The Weyburn Midale Pool is located on the northern flank of the Williston Basin in southeastern Saskatchewan. The reservoir is in the Mississippian Midale Beds at a depth of more than 1370 m (4500 ft) below surface (Figure 1). At the Weyburn Midale Pool, the sub-Mesozoic unconformity truncates the Ratcliffe Beds and the Midale Evaporite.

The Midale Beds are sub-divided into three main units, which are, from stratigraphically lowest to highest: the Frobisher Evaporite, the Midale Vuggy, and the Midale Marly. The Midale Marly is overlain by the Midale Evaporite, which forms the basal unit of the Ratcliffe Beds. The Midale Marly, the Midale Vuggy, and the Midale Evaporite form a shallowing-upward carbonate sequence deposited in an arid, tidal-flat environment. Subtidal shoal and intershoal deposits at the base are overlain by intertidal inner shelf (lagoon) deposits, which are, in turn, overlain by supratidal evaporitic deposits (Churcher and Edmunds, 1994). A modern example of the arid tidal-flat environment is found in the Turks and Caicos Islands, south of the Bahamas.

a) The Midale Evaporite

This unit, which acts as the reservoir top-seal, is 4 to 7 m (13 to 23 ft) thick and is laterally continuous (Churcher and Edmunds, 1994). It is characterized by massive, bedded and nodular anhydrite.

The Marly Unit

The Marly unit is 0.9 to 9.1 m (3 to 30 ft) thick within the study area. Its porosity ranges from 20 to 37% and permeability ranges from 0.1 to 150 md (Churcher and Edmunds, 1994). It is characterized by microcrystalline to microsugrosic dolostone interlayered with fine-grained argillaceous beds. The dolostone texture varies from mudstone to wackestone. Observations made during core examination indicate that the unit represents a low-energy shelf environment with deposits ranging from outer shelf wackestones to inner shelf mudstones to restricted lagoonal mudstones to tidal-flat evaporites.

The Vuggy Unit

The Vuggy unit is 9.1 to 21.3 m (30 to 70 ft) thick and is composed mainly of limestone (Churcher and Edmunds, 1994) that contains numerous macro-scale vugs up to 1.3 cm (0.5 in) in diameter from which it derives its name. Porosities and permeabilities respectively range from 2 to 15% and 0.01 to 20 md in intershoal mudstones and wackestones, and from 10 to 21% and 1 to 500 md in shoal-derived packstones and grainstones that are particularly vuggy (Churcher and Edmunds, 1994). Diagenetic features include large, jagged stylolites, anhydrite-infilled vugs and fractures, and brown metasomatic anhydrite. Metasomatic anhydrite nodules have been interpreted as products of a late-stage diagenetic event associated with oil migration in the Late Cretaceous and Tertiary (Kendall and Walters, 1978).

Underlying the Midale Vuggy unit are the Frobisher Evaporite and equivalent beds, which, with the Frobisher Marly and the Frobisher Vuggy, represent another distinct shallowing-upward sequence. Either the Frobisher Evaporite or the equivalent Frobisher Marly unit was observed in most cores in this study. Churcher and Edmunds (1994) believed the original oil-water contact for the reservoir was in the Frobisher Beds.

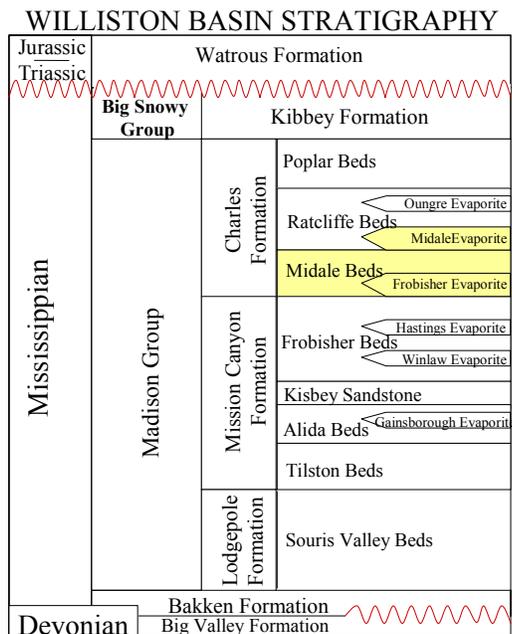


Figure 1 - Williston Basin stratigraphy in southeastern Saskatchewan (modified from Churcher and Edmunds, 1994).

3. Initial Core Observations and Analysis

Fourteen cores have been studied. Core locations are restricted to within the RCP study area of 6.6 km². Further investigation may, however, benefit from a more regional perspective and would involve geologically interpreting additional cores adjacent to this area. Figure 2 shows the location of the Weyburn Oil Field and the outline of the RCP study area wherein seismic data were acquired. The cores studied thus far are from wells 1/12-7-6-13W2, 1/16-12-6-14W2, 1/6-13-6-14W2, 41/8-13-6-14W2, 1/6-18-6-13W2, 1/16-13-6-14W2, 1/4-13-6-14W2, 1/2-24-6-14W2, 1/10-13-6-14W2, 1/2-13-6-14W2, 1/8-14-6-14W2, 1/8-24-6-14W2, 1/8-18-6-13W2, and 1/10-12-6-14W2 (Figure 3). These wells were chosen for their diverse areal coverage and are located at sites that are known, from seismically rendered maps, to be of interest. Most cores were about 18.3 to 30.5 m (60 to 100 ft) long, and included both the Marly and Vuggy zones, as well as part of the underlying Frobisher Beds, and, in some cases, the overlying Midale Evaporite. One exception was the core from well 8-18-6-13W2, which, according to log tops, began about 6.1 m (20 ft) below the Marly/Vuggy contact. A second exception was the core from well 8-24-6-14W2, which was so highly sampled and fragmented that only about 18.3 m (60 ft) of the original 34.1 m (112 ft) recovered were present, making depth measurements unreliable. Through synthesizing the core-based facies data, a preliminary geological model of the lateral and vertical heterogeneities present on the local scale can be made.

During core analysis, the Marly/Vuggy contact, based on gamma-ray and resistivity well logs, correlated well with the first appearance of vugs in most of the cores. The contact between the Midale Marly and the underlying Midale Vuggy was apparently an exposure surface which, due to porosity and permeability values that vary across the surface, has inhibited fluids from flowing from one zone to another. At the scale of the study area, and for the purpose of monitoring fluid flow, the heterogeneity throughout the reservoir that is evident from core studies is an important feature. In the Marly zone, most wells show 3 to 4.6 m (10 to 15 ft) thick intervals of massive, oil-stained, bioturbated, microskeletal dolowackestones with varying degrees of fracturing and argillaceous laminations.

The facies in the Vuggy zone range from ostracod-peloid mudstone and wackestone (intershoal) to skeletal lime packstone and peloidal lime grainstone (shoal). Core studies show that small-scale stacking patterns from shoal to intershoal are recognizable, suggesting the presence of high frequency shallowing-upward events. Also, stylolites, fractures, and anhydrite plugging are common. Often, stylolites are associated with fractures, especially those filled with anhydrite (Figure 4).

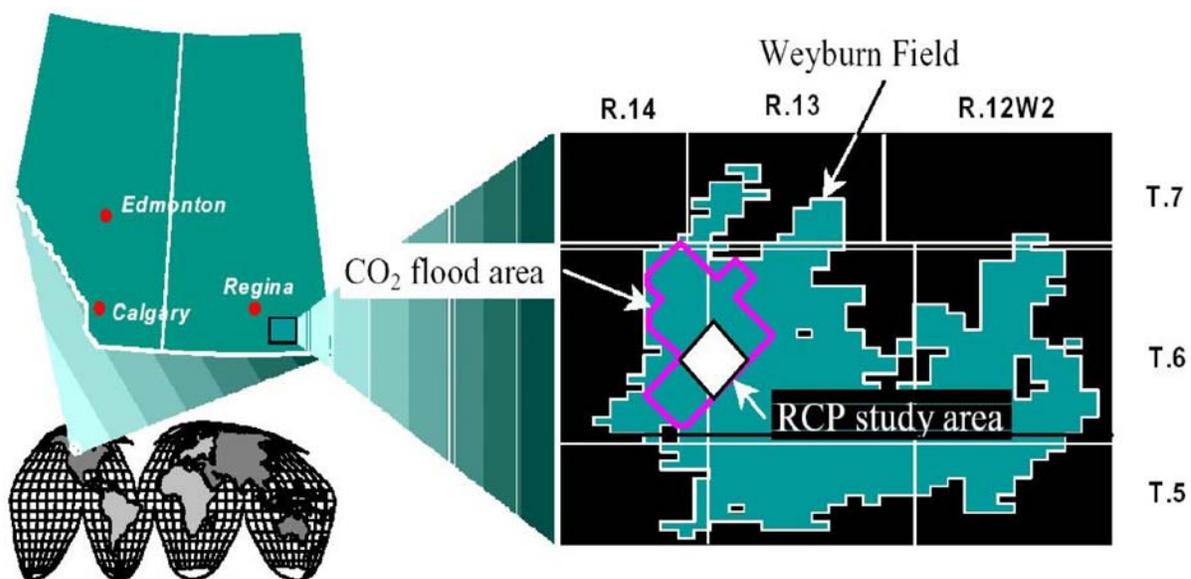


Figure 2 - Location of RCP study area (Brown, 2002).

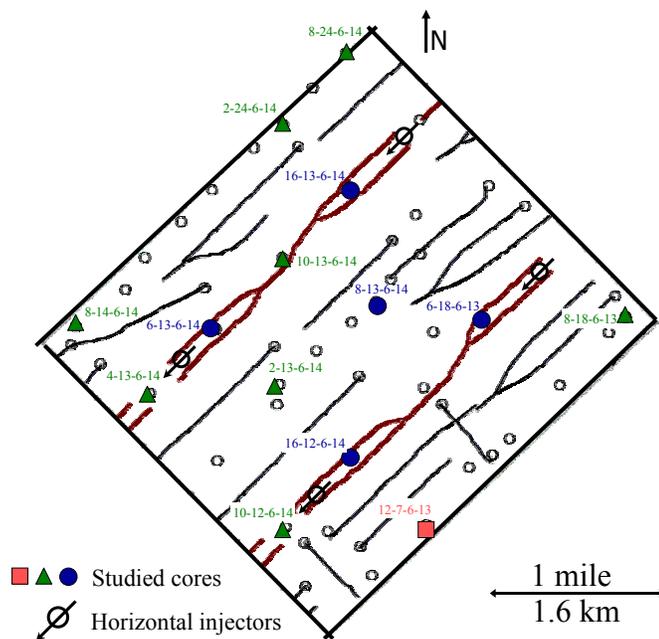


Figure 3 - Plan view of wells in the RCP study area, Weyburn Midale Pool. The square represents the first core studied in fall 2002; circles indicate the cores studied in March 2003; and the triangles indicate the cores studied in August 2003.

Fractures are of great importance when considering fluid flow in this reservoir. Fracture distribution observed in a few vertical cores may not be representative of the whole reservoir, limiting the interpretation of fracture density and orientation. The Midale Vuggy is known to be more fractured than the Marly, although the Marly contains fractures at a thin-section scale. A study of the heterogeneous distribution of the fractures should help answer some questions of interpretation revealed by seismically rendered maps. For example, core from well 8-13-6-14W2 shows relatively few vertical fractures, yet that from other wells, such as 6-13-6-14W2, has numerous vertical fractures. Using methods of fracture detection and quantification from cores and borehole images, the Vuggy intershoal facies has been found to contain more fractures than the

shoal facies (Bunge, 2000). This observation was confirmed in this core study at most wells. The intershoal fractures consist of vertical, as well as shattered fractures in the mudstones and wackestones. Where fractures were observed in the shoal facies, especially in the grainstones, metasomatic anhydrite is usually present, sealing the fractures and permeating into the adjacent matrix.

Another interesting feature discovered while studying the cores is the presence of oil in the lower Vuggy zone. In core from well 6-13-6-14W2, the contact between the Vuggy and the underlying Frobisher-Alida beds was placed at the base of a 1.5 m (5 ft) thick anhydritic limestone bed overlying dolostone (Figure 5). Oil was observed above and below this anhydritic limestone, and vertical fractures were present above and below the Midale/Frobisher contact. This may explain why the corresponding acoustic impedance maps show a downward trend in CO₂ injection in the western region, for fractures may act as conduits that carry the CO₂ into the lower beds. In Figure 5, variations at the Vuggy/Frobisher contact are observed in core from two wells located in adjacent sections.

After initial observations were completed, construction began of cross sections and structural and stratigraphic models. By using core interpretations to create structural depth slice maps every 1.5 m (5 ft) from 1399 m (4590 ft) to 1448 m (4750 ft) below KB elevations, a preliminary schematic diagram of facies relative to present day structure was created (Figure 6). This diagram showed that the vertical and lateral distributions of shoal and intershoal deposits are more

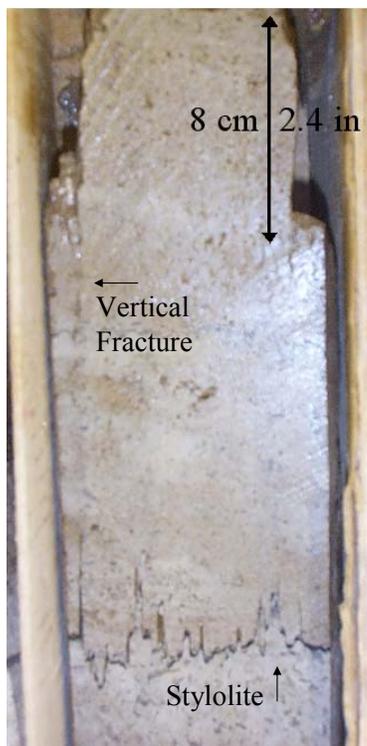


Figure 4 - Stylolite and vertical fracturing at well 6-18-6-13W2 in the Midale Vuggy shoal facies.

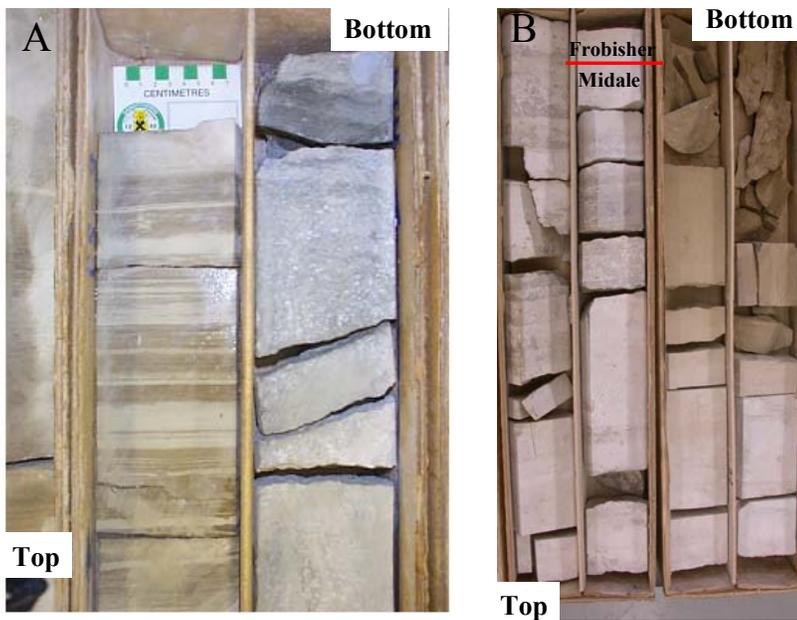


Figure 5 - Variations in the Vuggy/Frobisher contact.
 A) Core from well 16-12-6-14W2 with typical layered and mottled anhydrite [the Vuggy/Frobisher contact is not seen in this picture as it is 0.6 m (2 ft) above the top at 1444.8 m (4740 ft)];
 B) Core from well 16-13-6-14W2 shows vertical fracturing above and below the contact, from anhydritic limestone in the Midale, to oil-stained dolostone in the Frobisher [the Midale/Frobisher contact is marked by the red line at 1436.2 m (4712 ft)].

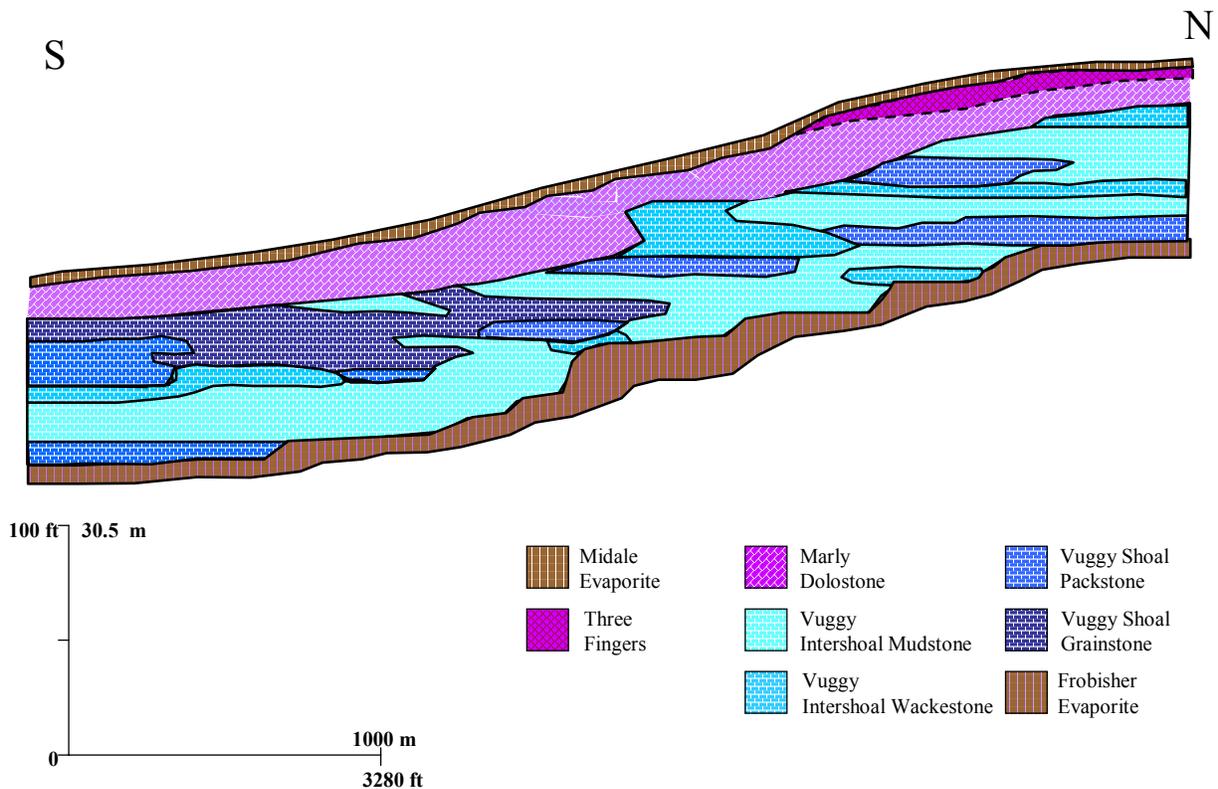


Figure 6 - Schematic diagram, based on core observations, of present-day structure within the RCP area (note vertical exaggeration).

complex than originally modeled. The shoals are not interconnected, being separated by intershoal facies with varying degrees of porosity and permeability. However, as explained earlier, fractures in the intershoal facies act as high-permeability conduits between the shoals. The complexity of the Marly is at a much finer scale than that seen in the diagram, so more work will be done to define continuous flooding surfaces, argillaceous beds and other features that will enable a facies analysis of this unit to be made. This also holds true for the Vuggy. Logs such as neutron-density, gamma ray, resistivity, and SP will be examined and compared to results from core observation in order to enhance vertical resolution. Once smaller depositional units are defined, the logs can be correlated to other uncored wells in the RCP study area to refine the lateral facies boundaries.

It is important to note that the structural slices do not follow depositional time lines. By using a method of creating pseudo-structural slices hung from a stratigraphic datum, a more precise tie from structure to depositional stratigraphy may result. For this correlation, a good horizontal marker must be used, determined from further core analysis and log ties. A flooding surface within the Marly is laterally continuous and should work well as a datum once it is correlated in all wells. By correlating depositional cycles at various scales and representing those facies present at either maximum transgressions or regressions, true reflected heterogeneity and preferred fluid pathways in the absence of fractures might be recognizable (lateral movement of fluid in a reservoir follows stratigraphic facies rather than structural topography). To create a pseudo-structural model, the cross section will be flattened on a stratigraphic datum, and will be built from slices taken every 1.5 m (5 ft) above and below this datum.

Using information obtained from studying the cores, facies will be correlated between wells. The Marly and Vuggy zones are easy to identify in both the logs and cores. From there, smaller intervals will be correlated such as the widespread flooding event that occurs in the lower Marly, and spatial correlation (if any) will be made between metasomatic and nodular anhydrite in the Vuggy zone. In addition, the shoal/intershoal relationship within the Vuggy will be refined, the nature of the Marly/Vuggy and Midale/Frobisher contacts examined, fracture distribution re-analyzed, and facies variations within the Marly that may hinder efficient sweep mapped.

This work will be performed using core data followed by log data, which will enable it to be extended beyond the limits of the RCP study area, thus providing a broader look at the reservoir region. Once the geologically rendered models are complete, they will be integrated with the geophysically rendered attribute maps to define facies distribution.

4. Seismic Attributes

From October 2000 to October 2002, three multi-component seismic surveys were conducted at Weyburn. The first, or baseline survey, was acquired as CO₂ flooding began. Subsequent monitor surveys were acquired in October 2001 and October 2002. Interpretations are based on the observed time-lapse anomalies and attributes; however, the reservoir is represented by only half of a wavelength in the seismic data, making large-scale interpretation difficult. Although the rock properties of the Marly and Vuggy are quite different, they are often averaged together for the interpretation of seismic attributes.

The p-wave amplitude map (Figure 7) shows a high-amplitude anomaly in the western region and a low-amplitude anomaly in the central and northern regions. Variations in the Marly zone may show links between the geology and the seismic response of the amplitude map. Well 41/8-13-6-14W2 contains thinly interbedded limestones and dolostones within the lower Marly zone that may correlate to the low amplitude anomaly. The westernmost core (from well 8-14-6-14W2) shows a 6.1 m (20 ft) thick interval of massive, bioturbated skeletal dolostone with only one thick argillaceous layer, and in the western portion of the amplitude map, a high-amplitude anomaly is present. The entire interval has a moderate to heavy oil stain. With further interpretation and integration of seismic attributes to rock properties, the p-wave amplitude map should help to delineate geologically the areal extent of good and poor reservoir in the Marly unit. This is especially important as most of the remaining oil is within the Marly.

Acoustic impedance difference maps of the Marly and Vuggy (Figure 8), created from data obtained in the 2001 pool monitor survey and the 2000 baseline survey, show up to 10% change in impedance at the injectors and producers with high CO₂ injection rates and good responses. Little to no change is observed near the northern injector. The most visible distinction is in the western injector, where no change is observed in the upper Marly, but a significant difference is seen in the Vuggy. Since acoustic impedance is the product of velocity and density, changes in impedance might imply changes in fracture density, changes in porosity, or anhydrite plugging. Core studies suggest that the change in impedance seen here indicates that CO₂ is not entering the Marly, but is finding a pathway (probably through vertical fractures) that allows CO₂ to migrate downwards in to the underlying Frobisher Beds.

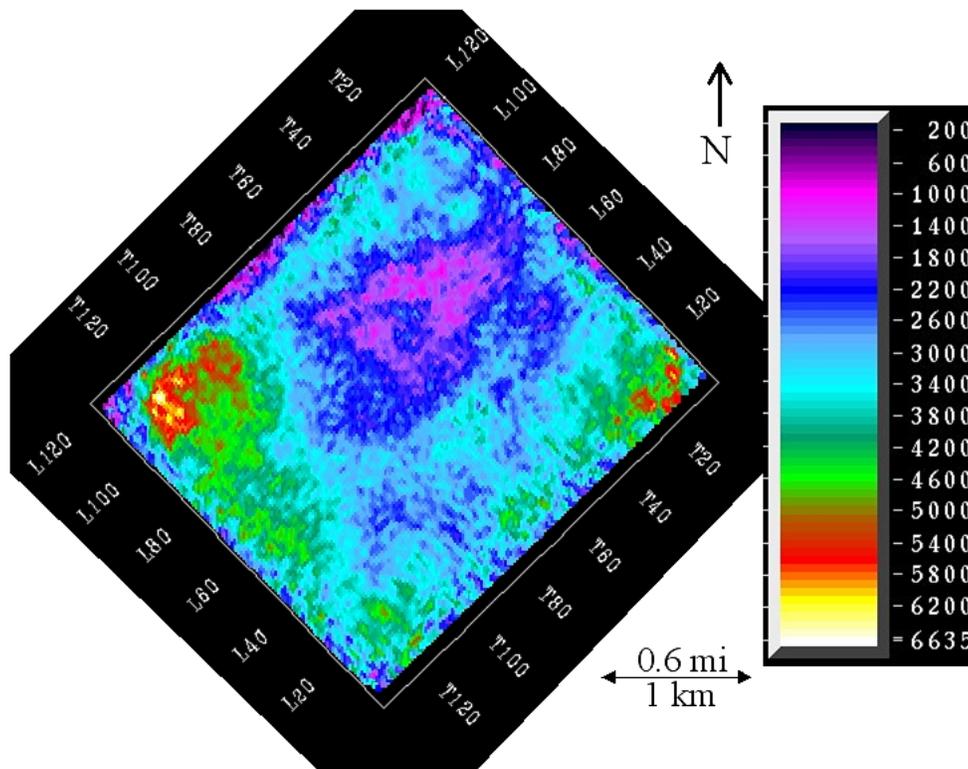


Figure 7 - P-wave amplitude map; note large, low amplitude in the centre, and high amplitudes to the west, south, and east.

Core from wells 16-12-6-14W2, 6-18-6-13W2, and 12-7-6-13W2 show thick intervals of massive, oil-stained dolostone and highly fractured Vuggy zones. These wells are located in areas of high injection and good production. The fractures in well 6-13-6-14W2 may act as flow conduits into underlying beds. This would explain the high injection but poor production in the western region and corresponds to the impedance results.

Well 16-13-6-14W2 features low injection and poor production rates, but shows a massive Marly pay zone, an upper Vuggy intershoal, and typical Vuggy packstone, wackestone, and mudstone with fractures. There is no excessive anhydrite to explain the low production. Injection rates in the area (Figure 9) are generally high in the south, and much lower in the north. This issue requires further study.

To understand which geophysical attributes are directly related to the reservoir geology, cross-plots of seismic attribute versus rock properties will be generated. For example, by obtaining a numerical value for a specific attribute at a well (keeping in mind the low resolution of the seismic data such that the entire Midale Beds are represented by half of the seismic wavelength), and then plotting it against the observed average value of a specific property of the reservoir at that well (e.g., porosity), a clear trend may be obtained. If this is accomplished, then interpretation of the attribute maps will correlate to the geology. Attributes for cross-plotting will include p-wave impedance, p-wave amplitude, and frequency decomposition. Rock properties, especially porosity and permeability, will be obtained from cores. Properties will also be obtained from density-neutron, gamma ray, and resistivity logs.

5. Conclusions

Given the low vertical resolution of the seismic data for the Midale Beds, additional methods are required to determine geology and its effect on fluid flow. A detailed study of cores shows a great deal of vertical and lateral heterogeneity on a very local scale. By creating stratigraphic and pseudo-structural cross sections based on core and log data, preferred fluid pathways may be determined, and a better understanding obtained of geological influences on seismic data. Cross-plots of rock properties and seismic attributes should further define which seismic attributes could be used for geological characterization of a thin reservoir.

P-impedance changes

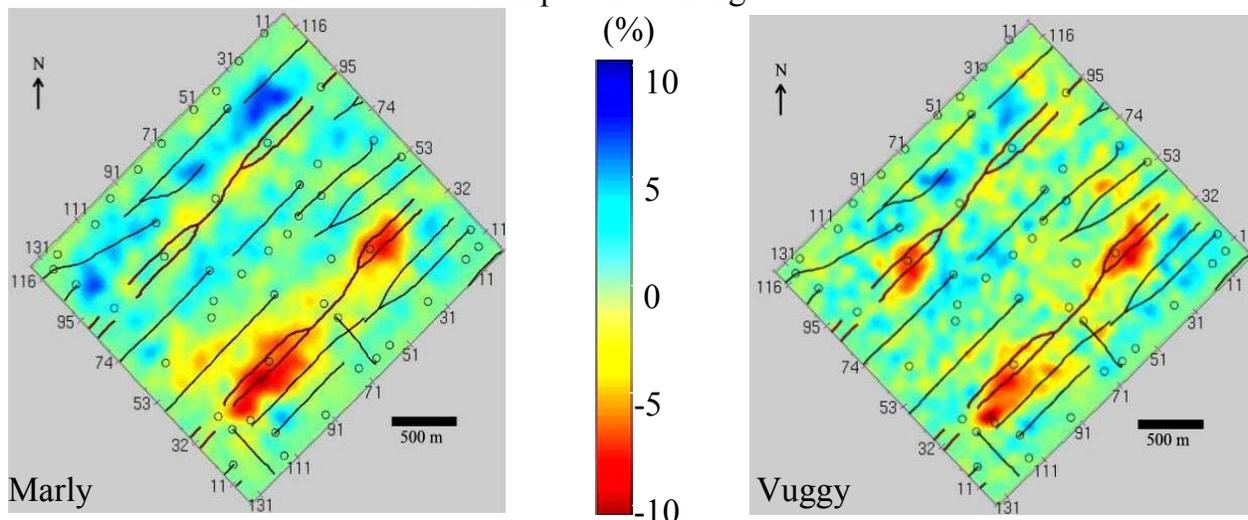


Figure 8 - Acoustic impedance difference maps (monitor survey 2001 minus baseline survey 2000) generated by Herawati (2002). The anomalies indicate change in impedance in response to the CO₂ flood; note the change in the western injector of the Vuggy unit that is not apparent in the Marly unit.

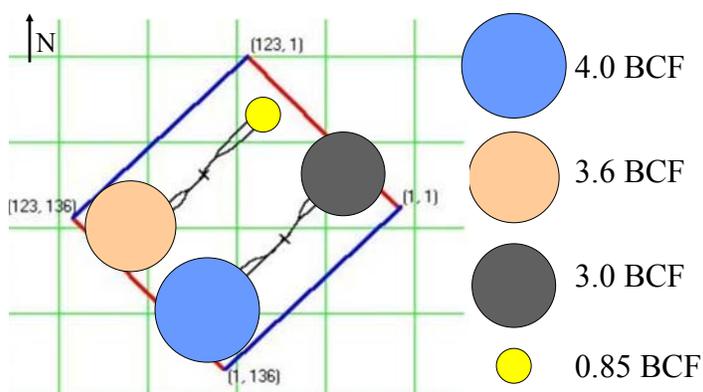


Figure 9 - Cumulative injection rate of CO₂ up to August 2002 (courtesy of EnCana Corporation).

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